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Subvisual Cirrus: What It Is and Where You Find It

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Subvisual Cirrus:
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ABSTRACT

Extremely low column density ice clouds (subvisual cirrus) have significant impacts on passive IR remote sensing of both the atmosphere and the Earth. In this paper I review the physical properties of subvisual cirrus and discuss their detection and global distribution.

1. INTRODUCTION

High, thin, nearly invisible cirrus has been known for years. Uthe[1], Barnes[2,3], Heymsfield[4] describes observations over Kwajalein where pilots and lidars could clearly see the cloud but DMSP and ground observers could not. Such clouds have come to be known as subvisual cirrus (SVC). Subvisual cirrus found in the tropics is sometimes called high altitude tropical (HAT) cirrus[5]. Sassen [6,7] and his collaborators present valuable new results on SVC. Additional important information about SVC can be found in Flatau[8], Liou[9], Takano[10], Platt[11], Hutchinson[12,13], Schmidt[14] and Dalcher[15].

The term "cirrus" refers to a principal cloud type with morphologically distinct features. Cirrus is defined as detached clouds that appear as thin (without self-shadowing),white, fibrous tufts usually showing delicate filaments, often with considerable vertical extent. Cirrus is composed of ice crystals and its optical morphology is a result of glaciation, ice crystal microphysics and the interaction of falling crystals with atmospheric winds.

Most people correctly equate "cirrus" to "ice crystal cloud", but not all ice crystal clouds are cirrus. In the winter, most polar continental stratoform clouds are made of ice (or are mixed phase) yet they have no visual resemblance whatever to cirrus. The same is true for ice fogs ("diamond

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dust"). In this paper subvisual cirrus will mean any ice cloud whose optical depth is small (< 0.1 in the visible).

Subvisual cirrus is of interest for a number of reasons. Being nearly transparent, SVC is difficult if not impossible to detect with automated cloud detection algorithms whose optical depth limit is nominally 0.1 in the visible[16,17]. Cirrus is also thought to be a major factor in controlling the earth's radiation budget. Finally, small ice particles (the kind thought to comprise much SVC) are difficult to detect with *in situ* probes and thus even direct attempts to sample such clouds are difficult.

The goals of this paper are to review SVC and to suggest that they are a common and distinct subclass of cirrus clouds characterized by a relatively narrow range of physical properties.

2. HISTORY AND CONCEPT OF SUBVISUAL CIRRUS

The US Army's Kwajalein Missile Range (KMR now known as USAKA - United States Army Kwajalein Atoll) in the Marshall Islands has played an important role in identifying and studying SVC. Kwajalein is located in the western Pacific ocean near 167° W, 9° N and its weather is dominated by the intertropical convergence zone (ITCZ) where the tropopause can be high, sometimes reaching 60,000 ft. During 1986 the author was part of team using NASA's Learjet to make various measurements of cirrus clouds, IR backgrounds and Halley's comet in Kwajalein[18]. During our daytime flights, the aircraft routinely reached 45,000 ft pressure altitude (about 47,000 ft MSL) and cirrus was present above us most of the time between March and September. In many cases the 22° halo was present and on at least one occasion a parhelion was observed. The former observation tells us that the crystals had well developed 60° prism faces and the latter tells us that large (> 30 μm faces), oriented plate crystals were present[19].

Kwajalein Chief Meteorologist (in 1986) Don Thornley tells the story of how post-WW II high altitude aircraft (for the time) flying at 35,000 ft reported a thin layer of cirrus "just above us". As planes got better and the ceilings raised, the pilots reported the same thin cirrus just above them at 40,000 ft, then later 45,000 and still later at 50,000 ft. The repeated anecdotes of cirrus that was always just out of the aircraft's altitude ceiling lead to the term *cirrus evadus* . Sounding rockets verified that there was usually a thin layer of cirrus at the tropopause (55,000 ft typically) when the ITCZ was over Kwajalein. This layer was as little as 0.5 km thick and was rarely if ever reported by ground observers.

All but one of the handful of studies of SVC have taken place at Kwajalein. It is possible than the conclusions based upon such data may be only valid for the eastern Pacific and not

representative of other places in the world.

3. "VISUAL" ASPECTS OF SUBVISUAL CIRRUS

The term "subvisual" suggests that a human observer cannot detect the clouds. In general this is an apt description, although solar scattering angle, cloud structure and line-of-sight viewing angle also play important roles. Clouds whose contrast away from the sun is below the visual threshold brightness can be seen without difficulty when viewed close to the sun. This is a result of the well-known forward scattering properties of particles whose size parameters are large (> 10) regardless of their shape. Owing to the absence of any visible structure for the eye to seize upon, a completely uniform cover of thin cirrus might pass unnoticed even to a trained observer even though the cloud's brightness exceeded the visible threshold. Even without some density structure, some uniform cirrus makes its presence known only by showing halos, usually parhelia or the 22° halo.Very thin (but still visible) cirrus is sometimes called "blue cirrus" because it does not scatter enough white light to appreciably alter the much brighter blue background skylight. Finally, SVC is usually only about 1 km thick but may be many km wide. Therefore a vertical viewing angle will pass through far less material than will one which is nearly horizontal. This explains why pilots can often see thin cirrus as they fly towards or through a thin cloud but ground observers cannot. It also explain why thin clouds are always more visible near the horizon than overhead.

Cirrus whose visible optical depth is less than about 0.1 could well be missed by both ground and satellite observations. Sassen[6,7] suggest that the boundary between subvisual cirrus and visible cirrus is about $\tau = 0.03$. This compares favorably with the findings of Platt[11] who find $\tau = 0.06$ for visible but hazy cirrus.

4. GLOBAL DISTRIBUTION OF SUBVISUAL CIRRUS

The global distribution of subvisual cirrus is virtually unknown. Cirrus climatologies, however, have been done and they reveal that cirrus displays mesoscale organization[20,21,22]. To the extent that SVC is correlated with ordinary cirrus, we can use the latter as a guide (Table 1 lists cirrus global frequency distribution studies). Ordinary cirrus is concentrated near the equator (ITCZ) where deep convection occurs, and at midlatitudes, where it is associated with frontal boundaries. The global frequency over land is about 23%. The zonal frequency varies from between 5 and 40%. Because most studies do not detect subvisual cirrus, the numbers quoted above must be viewed as lower limits if applied to SVC. There is some evidence that subvisual cirrus may be much more common than previously supposed and may be ever-present in some parts of the world. This notion is reinforced by LIDAR observations that often show cirrus when

no other probe detects anything. Quoting Barnes[3] "We found that thin cirrus was present almost all of the time at Kwajalein." Owing to the present limitations of visual observers and cloud detection algorithms, it is possible that high, thin cold cirrus could have been present during all of the studies listed in Table 1 without being detected.

TABLE 1 - CIRRUS GLOBAL DISTRIBUTION STUDIES

STUDY	DATA
Barton[23]	NIMBUS-5
Woodbury[24]	SAGE/AEM
Woodbury[25]	SAGE/AEM
Chiou et al. (1990)[26]	SAGE/AEM
Henderson-Sellers[27]	Gound based/METEOSAT
Prabhakara[28]	NIMBUS-4
Menzel and Wylie[29]	GOES/VAS
Menzel and Wylie[30]	HIRS/NOAA-10,11
Rossow and Schiffer[31]	ISCCP
Warren[32,33]	Surface Obs
Wylie[34]	GOES/VAS
Wylie[35]	GOES/VAS

5. MICROPHYSICAL PROPERTIES OF SUBVISUAL CIRRUS

The most complete observations of subvisual cirrus are given by Sassen[6,7], Heymsfield[4] and Barnes[2,3]. While the first two reports were in fairly good agreement with each other, the latter reported measurements of tropical SVC showing that two types exist: those with particle radii less than about 10 μm (in agreement with later work) and those with particles larger than about 100 μm. While one might expect SVC to have almost any range of particles sizes, Barnes demonstrated that a large fraction of tropical SVC is composed of small particles. The microphysical aspects of their work is summarized in Table 2 and 3 along with related properties of all cirrus clouds reviewed by Dowling[36]. To the extent that we can believe any trend suggested by only two studies, we can say that subvisual cirrus is:

TABLE 2 MEASURED PROPERTIES OF SUBVISUAL CIRRUS

location	Kwajalein	Wausau, WI	Kwajalein	Kwajalein	Regular Cirrus
long, lat.	167.7 E, 8.8 N	89.63 W, 44.93 N	167.7 E, 8.8 N	167.7 E, 8.8 N	
time-of-year	Dec 17, 1973	Oct 21, 1986	various	various	
time-of-day	9-17 local	7:45 - 9 am local	various	various	
topography	Pacific atoll	mid cont. grassland	Pacific atoll	Pacific atoll	
climatology	ITCZ, trades	jetstream, frontal	ITCZ, trades	ITCZ, trades	
top-base (km)	16.7 - 16.2	12 - 13,broken			9 (4 - 20)
thickness (km)	0.5	~1 0			1.5 (0.1 - 8)
trop height (km)	16.7	12.8			
instrumentation	L,A,S,V	L,C,S,V	L,V	L,V	
pressure (mb)	108 - 99				
temperature (C)	-83	-65 - -62			
IWC (g m^{-3})	1 x 10^{-4}	2 x 10^{-4}	10^{-9} - 10^{-8}	(10^{-4} - 10^{-5})	2.5 x 10^{-2} (10^{-4}-1.2)
crystal type	trig. plts/col (~1:1)	~spherical			
crystal size (µm)	5 - 50 (mean 5)	mean 25	mean 2	~500	250 (1-8000)
num dens (m^{-3})	5 x 10^4	2.5 x10^4	10^3 - 10^4	< 1	(3x10^4) (10^{-1} - 10^7)
reference	[2]	[3]	[4]	[4]	[1]

instrumentation:
- A - aircraft
- C - camera
- L - lidar
- P - particle sampler
- S - sonde
- V - visual observer

references:

[1] Dowling and Radke (1990)
[2] Heymsfield (1986)
[3] Sassen, Griffin and Dodd (1989)
[4] Barnes (1982)

There is clearly a strong observational bias towards cirrus over Kwajelain. Dowling and Radke (1990) conclude that "The measured ranges displayed by the various properties show that cirrus clouds [*not subvisual cirrus*] defy comfortable characterization by any single set of numbers." Sassen and Cho (1993) note that "Climatologically, subvisual/thin cirrus appear to be higher, cooler, more strongly depolarizing than previously reported midlatitude cirrus, although similar $k/2\eta$ that decrease with height and temperature are found." (k = backscatter-to-extinction ratio, η = multiple scattering correlation factor)

1. almost always found at or near the tropopause, at least at low and midlatitudes.
2. composed of small (< 10 μm radius), nonspherical ice particles
3. optically thin
4. small vertical extent

Items 3 and 4 above suggest that SVC is virtually isothermal.

We suggest that the observed range of properties of subvisual cirrus is sufficiently restricted to identify them as a well-defined subclass of ordinary cirrus. This is not to say that subvisual cirrus cannot be found well below the tropopause or with large crystals. Indeed, thin, midlevel cirrus, especially in a low humidity region where the particles were sublimating could well be subvisual. Our point is that thin,virtually invisible cirrus clouds routinely form and endure near the tropopause and have a number of consistent microphysical properties.

The greatest source of uncertainty in Table 2 and 3 involves the ice-water content, crystal type, size and number density. The measured IWC depends on correctly counting the particles. Yet both studies recognized that they were unable to count particles smaller than D = 10, where D is the largest dimension of the crystal. Most particle size distributions including those of Heymsfield[37] are heavily weighted numerically towards small particles, the slope of the logarithmic distribution being about -3.8 for the coldest particles.

6. MODELS OF SUBVISUAL CIRRUS

Any future model of subvisual cirrus must be consistent with the findings above. Given the properties listed in Tables 2 and 3, the simplest possible yet physically-meaningful subvisual cirrus cloud is one represented by an isothermal layer of (usually) small particles at a single temperature and height. The role of small particles has been discussed by Platt[38] and Takano[10].

Previous models have been produced by several groups. Shettle[39,40] implements a subvisual cirrus model in LOWTRAN7 in which the particles are treated as spheres. Liou[9] developed the SUBVIS code which was a LOWTRAN7-compatible cloud subroutine. They can also model the particles as hexagonal crystals for certain ranges of size parameter. The model explicitly treats thin cirrus clouds although their particle size distributions may have included larger particles than may be appropriate for subvisual cirrus.

7. DETECTION OF SUBVISUAL CIRRUS

The ability to detect SVC is clearly an important goal. Since neither visual observer nor existing passive satellite systems can reliably find thin cirrus, we must first learn how to find and

characterize subvisual cirrus by any means, and then apply the results to satellite systems.

A. *In Situ* Measurements (Aircraft) The most reliable method for detecting cirrus clouds is to fly through them, sample the particles and verify that they are made of ice. This method also allows the determination of particle size, shape, number density and cloud thickness. Alternatively, balloons can be used to sample clouds but this method is less reliable because the trajectory of the balloon cannot be controlled. Another direct sampling technique is to use dropsondes. These are instrumentation packages that are parachuted into the suspected cloud area from an aircraft. Both methods can measure all the state variables as well as sample the cloud particles. The advantage of *in situ* sampling is that you know what kind of particles you are dealing with. The disadvantage is that only a minute fraction of the cloud can be sampled and this involves gathering data over a period of time during which the cloud can change.

B. Lidars. The most flexible method for remotely sampling the cloud is to use a lidar[41]. Dual polarization lidars give depolarization information which can usually distinguish ice particles from water drops. Lidars can operate at any angle with respect to the zenith and both zenith and non-zenith observations are valuable in characterizing the particles' properties. Lidar directly measures the volume backscatter coefficient. Existing laboratory measurements and model calculations can then be used to compute the backscatter-to-extinction ratio, which then is used to calculate the transmission of the cloud. Ideally, two lidars should be used; one at visible wavelengths and the other in the 10 μm atmospheric window. This allows both a range of particles sizes to be more completely measured and also provides backscatter information to be obtained near the infrared wavelength region of interest. In order to calibrate the lidar, the temperature, pressure, humidity, etc must be known along the optical path. These data are normally obtained using sondes and therefore balloons and radar tracking equipment must also be available. The main advantage of a lidar is that backscatter as a function of height AGL can be directly measured and can therefore be directly related to the sonde data for inversion. Lidar can also sample a large volume of the cloud quickly so that ranges in the scattering properties s of the cloud can be specified.

C. Passive Infrared spectroscopy/photometry from the ground[42,43,44,45] or space[35,46,47] used in conjunction with cloud particle models can be used to detect cirrus clouds. Using models of atmospheric transmission and the measured state variables of the atmosphere, a transmission of the cloud can be calculated. The advantage of a passive system is its simplicity. The disadvantage is that no height information about the cloud is directly available and the transmission depends on large amounts of modelling. Furthermore, the presence of low-tropospheric and stratospheric particles unrelated to the cirrus cannot be determined or accounted for. Such aerosols can seriously confuse the inversion of data to derive cirrus cloud transmission, especially when the cirrus is thin or subvisual.

8. SUMMARY AND CONCLUSION

Cirrus cloud optical thicknesses have an enormous range and there is no *a priori* reason to believe that there is some physical process bounding them. There is, however, some evidence to suggest that a common and poorly observed subclass of cirrus exist near the tropopause whose visible optical depths are less than about 0.1 . This so-called subvisual cirrus (SVC) has significant impact on many aspects of remote sensing and atmospheric physics, although greater study is needed. Table 3 summarizes the properties of these clouds.

TABLE 3. SUGGESTED BASELINE SUBVISUAL CIRRUS PROPERTIES

composition	nonspherical ice particles
particle size (long dimension)	$< 50\ \mu m$
particle shape	plates, columns, bullets, clusters
number density	$< 5 \times 104\ m^{-3}$
thickness (Δ z)	< 1 km
height	12-18 km (at or near tropopause)
horizontal size	mesoscale (20 - 2000 km)
temperature	-50 C
temperature range	nearly isothermal
optical thickness (τ)	< 0.05 in visible
depolarization	0.5 - 0.8
IWC	$< 2 \times 10^{-4}\ g\ m^{-3}$

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Note added in Proof: Wylie and Menzel[48] argue that the average global occurrence of thin cirrus may be has high as 75%

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TECHNOLOGY OPERATIONS

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